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NEW WAVE-SHAPING CONCEPTS IN FRAGMENTATION MUNITIONS

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Most of the problems associated with high fragmentation munitions stem from the fact that one is faced with a set of conflicting requirements. On the one hand one wants a brittle material for good fragmentation characteristics at the target; on the other hand one needs a fairly tough material to withstand launch stresses and/or rough handling conditions.

Most of the research currently being conducted in this area falls into one of two categories depending upon the approach taken to resolve this dilemma. In the "natural fragmentation" approach different alloys, heat-treatments or processing techniques are employed to try to achieve a suitable balance between good fragmentation and structural integrity. With such techniques one tries to influence the fracture pattern on a microstructural level. In the "controlled fragmentation" approach, one tries to control the fracture pattern on a macro-scale by utilizing some form of notching of the inner or outer surface of a specimen made of a fairly tough material. This notching generally takes the form of mechanical or chemical removal of material in specified regions. A more subtle form of this approach is the metallurgical embrittlement of the specimen in a selected pattern. With this technique no material need be removed.

In this paper we describe a new technique which provides some attractive new options in making those tradeoffs which must be made when faced with a set of conflicting requirements. This new approach involves a method of controlling the form of shock waves induced in fragmentation munitions.* The shock waves are tailored in such a way as to deliberately induce a novel mode of fracture in such munitions. The result is a substantial increase (as much as a factor of five) in the number of fragments produced from a given exploding shell.

* is described

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The rationale for the wave shaping concept is based upon theoretical analyses using one-and two-dimensional elastic-plastic wave propagation codes which provide details of both the detonation wave in the explosive and the subsequent shock loading of the metallic cylinders. These calculations were initially used to predict that the proposed design would result in a novel mode of fracture within the shell wall. Later they were used to guide the optimization of parameters in an experimental program conducted to verify the theoretical predictions.

The experimental program consisted of an initial series of recovery shots of scale model cylinders in which the fragments were collected and size distributions were tabulated. In another series fragment velocities were measured. Finally, the role of material properties was investigated by conducting a series of tests involving steels whose characteristics range from those of tough, low-carbon steels through those of the newer high-fragmentation steels.

Results of the experiments confirm the theoretical predictions extremely well in terms of (a) the production of a new fracture mode, (b) a substantial increase in number of fragments, (c) optimum design configurations and (d) velocity of fragments produced.

WAVE PROPAGATION ANALYSIS

One of the factors limiting the pace of research in fragmentation munitions is that theoretical models of the stress distributions in an exploding cylinder are based upon a rough semi-intuitive picture of the sequence of events. Progress in this general area has evolved from empirical metallurgical approaches in which new alloys and special heat-treatment procedures are studied by explosively testing experimental cylinders to develop materials of enhanced performance. (1, 2) Both dynamic observations of the outside of exploding cylinders and post-mortem observations of the fragments are coupled into this approach.

It is known from high speed photographs of exploding cylinders that cracks begin to appear on the outer surface of the cylinder at an expansion ratio of approximately 1.2. On the other hand, complete breakup, as evidenced by "first smoke", does not usually occur until an expansion ratio of between 1.6 and 2.0. It is also known from post mortem examinations of recovered fragments that there are two characteristic modes of fracture: radial cracks (produced by tensile hoop stresses) and shear cracks. Radial cracks are initiated at a point within the casing close to the outer radius. They tend to be confined to the outer region except for extremely brittle materials. Shear cracks form later in time; they tend to initiate in the inner region and frequently link up with tensile cracks which develop earlier. Figure 1, taken from Clark and Juriaco (1) shows representative patterns of fracture behavior.

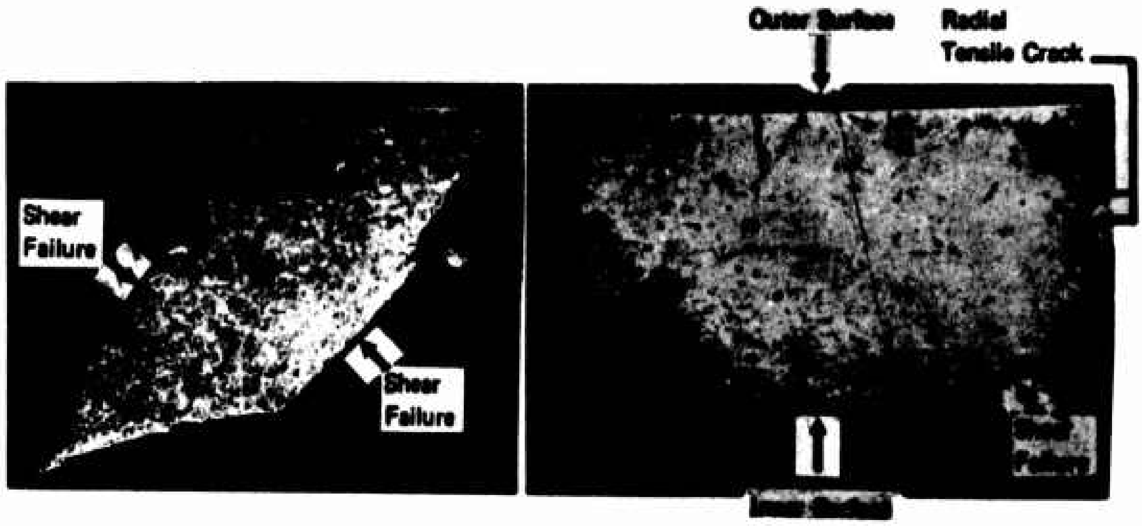


Figure 1. Typical Fracture Modes in Conventional Fragmentation Munition

The theoretical model developed by G. I. Taylor (3) assumed that fracture would be completely radial, i.e., controlled only by hoop stresses in the expanding cylinder. Hoggart and Recht (4) refined the Taylor model slightly by hypothesizing that the radial cracks serve as nucleation sites for extremely localized unstable thermoplastic shear bands which propagate into the inner region and eventually lead to complete separation across the shell wall.

While such approximate analyses do provide an intuitive picture of the stress fields operating, and do in fact predict some of the gross details of fragmenting cylinders rather well, they are deficient in several respects. They ignore wave propagation events and thus are unable to describe the time frame of the key element in fragmentation, viz. fracture initiation. It turns out that they also severely underestimate the stress levels producing the initial cracks. Finally, and most important, they provide little help in relating fragmentation performance to mechanical properties of materials.

A much more reliable and detailed description of the stress states developed in an exploding fragmentation round can be obtained from the one and two dimensional elastic-plastic wave propagation codes KO and HEMP. These codes have been documented elsewhere (5) and will be described here only by stating that they begin with the conservation laws, couple to these an equation of state for both the high explosive and the metal casing which is quite realistic for the high pressures (hundreds of kilobars) and short timeframes (microseconds) of interest here.

CONVENTIONAL MUNITIONS

Consider for example, the problem of a hollow metallic cylinder filled with high explosive which is detonated at one end at a point on the axis of symmetry. Obviously, complete details of the propagation of the detonation wave through the explosive and of the shock wave induced in the metal represent a two-dimensional time-dependent problem. If we restrict attention to a typical cross-section of the cylinder at a sufficient distance from the detonation point, the explosive may be considered to have been detonated instantaneously at each radial position (plane detonation) and the problem may be treated as one-dimensional with cylindrical symmetry. Results from a two-dimensional analysis indicate that results obtained with this approximation are indeed quite reliable when the assumptions indicated are met. For brevity and clarity we will discuss here only the one-dimensional results.

Good insight into the early wave propagation events taking place in a conventional round may be obtained by a study of Figure 2. The specific problem considered there is that of a hollow steel cylinder with an outer diameter of 4.22 cm. and a thickness of .36 cm. The cylinder is filled with Comp B explosive which is detonated simultaneously at $t = 0$ (plane detonation). The steel casing is treated as an elastic-plastic material with a moderate yield strength of 7 kilobars; a γ-law form of the equation of state was used for the HE.

As shown in the sequential curves of Figure 2, the high pressure field developed within the explosive by the conventional mode of detonation is relieved by a sequence of loading waves which propagate into the steel while a set of corresponding unloading waves moves into the HE. For convenience we plot only the radial stress in the steel; actually a triaxial state of stress exists in the steel. Because of the enormous pressure levels involved, however, this triaxial stress state is dominated by the hydrostatic pressure term.

When the initial compression wave induced in the steel casing reaches the outer surface it is reflected as a rarefaction wave which moves back toward the HE. This rarefaction wave reduces the radial stress to zero; it is important to note that it does *not* produce a *tensile* radial stress. Upon reaching the interface between the steel and the HE, the rarefaction wave sends a second relief wave into the HE and a recompression wave into the steel. ($t = 1.5$ μsec). This sequence of events is then repeated until a low ambient pressure level is obtained in both the HE and the steel or, as is usually the case, the cylinder bursts at an expansion ratio of about 1.8. One criterion for the accuracy of these theoretical calculations is to compare the

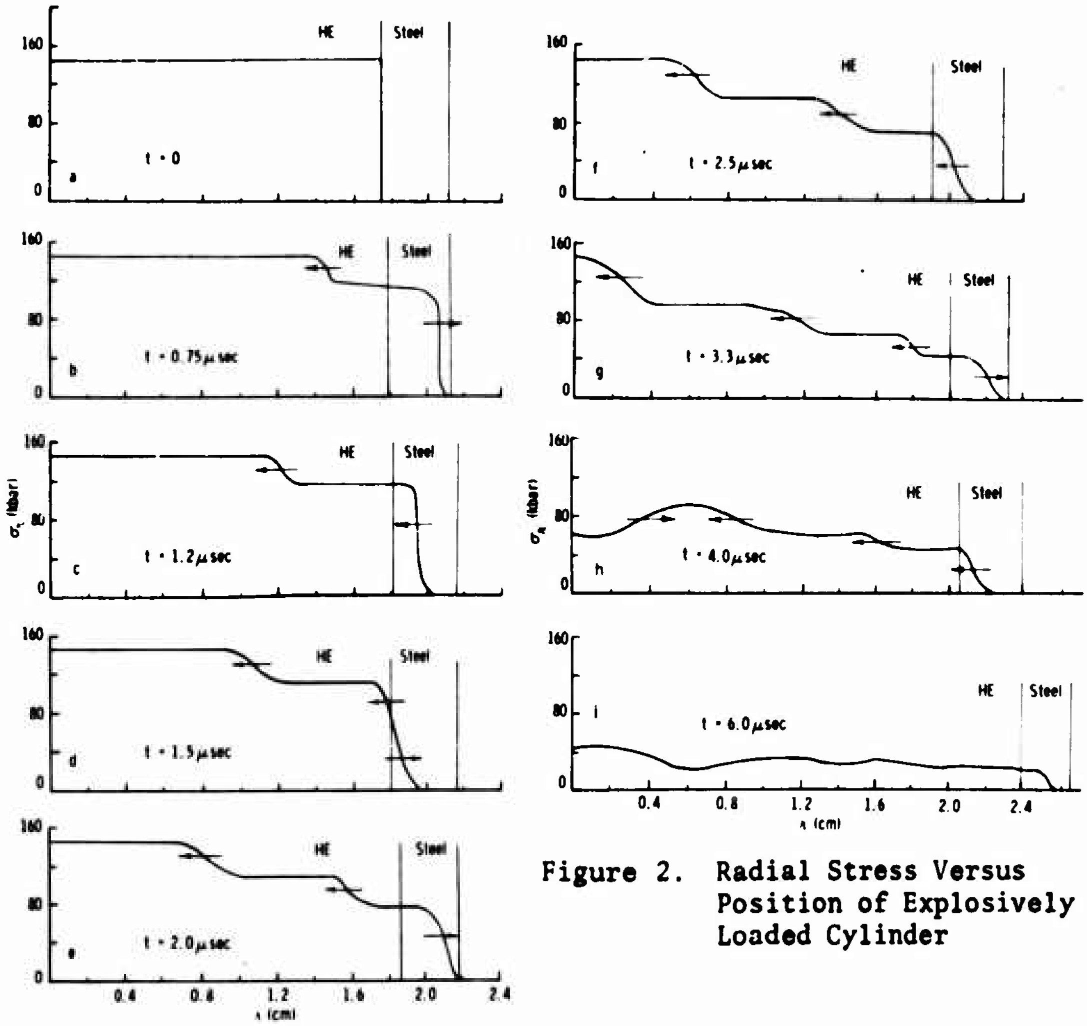


Figure 2. Radial Stress Versus Position of Explosively Loaded Cylinder

theoretical prediction of velocity with experimental measurements. The agreement is excellent as will be shown in subsequent paragraphs.

To relate these stress and velocity fields to the fragmentation process, it is instructive to plot the radial and hoop stresses as a function of time for two representative points within the casing wall, - one near the inner, one near the outer surface. (Figure 3) For points near the inner radius both stress components remain in compression for nearly the entire time frame of interest. On the other hand, for points near the outer radius the hoop stress becomes tensile during the first wave reflection; the radial stress remains compressive. Thus these wave propagation results explain the experimentally observed fracture patterns; in general, failure initiates by tensile fracture at subsurface locations near the outer radius, propagate outward toward the free surface and inward toward the explosive-metal interface. Their propagation inward is halted by the compression zone maintained there. Eventually these radial cracks serve as starters for intense shear bands which complete the fracture process.

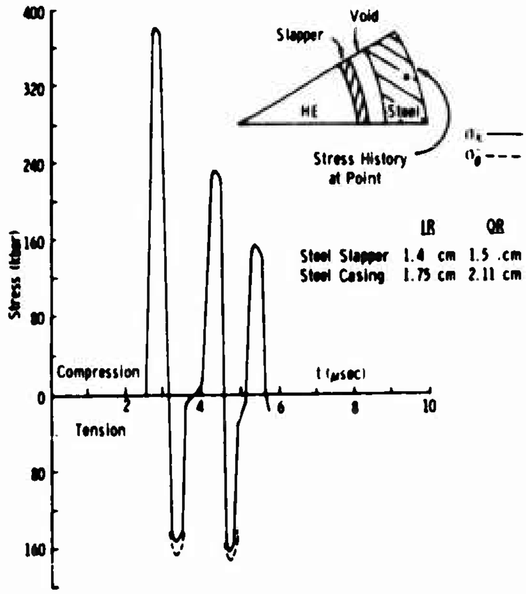
Of greater significance, these wave propagation results are also very illuminating in explaining why fracture by radial stress (spallation) is not a factor in conventional munitions. The radial stress simply does not exceed fracture stress levels during the tensile cycle.

THE SLAPPER CONCEPT

The analysis of the stress waves induced in conventional rounds makes it clear that the effect of the high pressure field exerted by the explosive products is to delay the introduction of a rarefaction wave from the *inner* surface until fairly late times. More graphically, the shell is subjected to a "long, steady outward push." The outward expansion does permit the hoop stress to become tensile near the surface, but the magnitude of such tension fields is much less than that of the initial compression field.

If the shock wave induced in the casing can be tailored in such a way as to permit a relief wave to enter from the inner radius at an early time and to interact with its counterpart from the outer radius, then a new mode of fracture can be induced, namely, spallation or fracture by the radial stress σ_r. This can be done in several ways. The most effective way is to introduce an inner slapper cylinder concentric with the outer casing but separated from it by an air gap.

Consider then the configuration sketched in Figure 4. End-initiated point detonation of the HE will produce plane detonation at typical cross-sections. This will accelerate the slapper across the gap; the resulting impact will send a shock wave into the outer casing. Details of this wave clearly depend upon the impact velocity, the relative impedances of the slapper and the casing, the relative thicknesses of the casing and slapper, and upon the width of the gap between slapper and casing. Use of the wave propagation codes referred to above allows one to analyze and sort out the role of these parameters without having to make dubious assumptions about any of them. Figure 5, for example, presents a results for σ_r and σ_θ as a function of time for the point indicated. These results are to be compared to Figure 3b which involves the same casing but not the use of a slapper. The increase in the level of tensile stress in both radial and circumferential directions is dramatic. This is particularly so when one compares the intensity and duration of these tensile stress waves with those



Stress Versus Time (r_0 = 2.0 cm)

Figure 3. Stress Histories Near Inner and Outer Surfaces of Explosively Loaded Cylinder

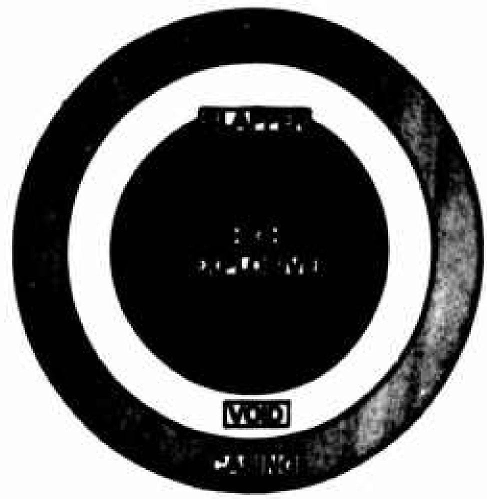


Figure 4. Cross-Section of a Slapper Configuration

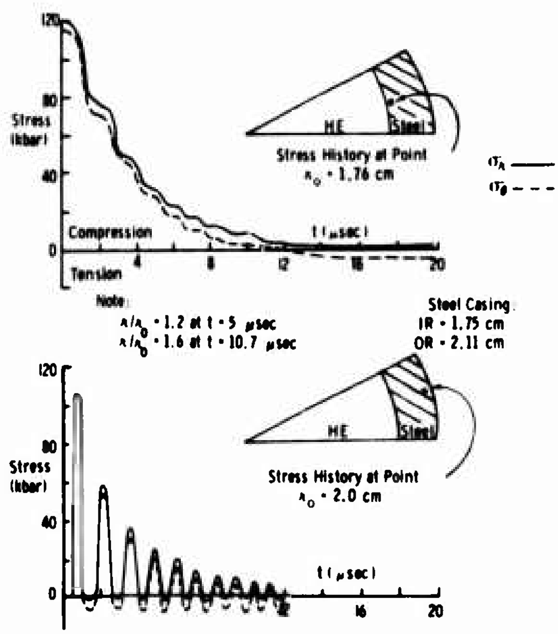


Figure 5. Stress History Near Outer Surface of Steel Casing in a Slapper Configuration

which have produced incipient spall in steel in a series of light-gas gun experiments. Butcher, for example, has found that for a pulse length of about 1.5 microseconds, 4340 steel at a hardness level of R_c 15 will begin to spall when the maximum tensile stress is about 25 kbar. For the same pulse length, but at a hardness level of R_c 52, the tensile stress required is closer to 40 kbar. It is clear that the tensile stress shown in Figure 5 will induce complete separation by spallation.

As was suggested above, use of a slapper configuration involves several parameters each of which may influence the resulting stress field (i.e. number of fragments produced) as well as the velocity of the fragments. An optimization study using the theoretical calculations was made before an extensive experimental program was undertaken. As a quantitative guideline for good fragmentation we used the accumulated damage concept in which one integrates the tension stress at a point with respect to time. Other, more sophisticated criteria could have been employed, but because of the extremely intense tension fields produced, the simpler approach was felt to be adequate in this initial study. The principal conclusions of this optimization study can be briefly summarized as follows:

a. Steel appears to be the best choice of material to be used in a slapper. There are tradeoffs to be made here which depend upon the impedance of a slapper (density X sound speed) and the velocity acquired before impact. Materials considered were polyethelene, aluminum, steel and tungsten.

b. Maximum velocities are obtained with very narrow air gaps and fairly thin slappers. One can achieve good fragmentation with such a design.

c. For a given amount of HE and a given outer casing, there is an optimum slapper thickness. (i.e. as the slapper becomes very thick it picks up less velocity before impact, thus causing less intense stress fields and less damage; on the other hand extremely thin slappers produce more intense stress fields but of shorter duration and therefore produce less damage).

EXPERIMENTAL RESULTS

An experimental program to validate the slapper concept was conducted by explosively loading steel cylinders using C-4 explosive. Fragments were recovered, sorted, examined for details of the fracture pattern and the fragment distribution parameters determined. In a preliminary set of tests using 1045 steel a good deal was learned about optimization of the slapper configuration. More than two hundred tests were conducted, the results of which are presented in substantial detail in reference 6. The primary set of tests employed both a 1026 steel similar to that used in production rounds and a high fragmentation steel (HF-1) recently introduced to enhance fragmentation characteristics. A very brief summary of experimental results is presented here in Table I. These tests used cylinders with an outer diameter of 1.75 inches and a length of 3.0 inches.

	NO SLAPPER	SMOOTH SLAPPER	GROOVED SLAPPER
1026 - CR	430	1245	2120
HF1 - QT	1200	2100	2400
HF1 - IT	1750	____	1840

Table I FRAGMENTS LARGER THAN ½ GRAIN

The benchmark tests (no slapper) provide a realistic indication of how fragmentation may be enhanced in full-scale conventional shells as the material is changed from the relatively tough commercial 1026 steel to the brittle high fragmentation steel HF-1 in either the quenched and tempered (QT) or the isothermally treated (IT) condition. An improvement of roughly a factor of four is obtained in both our small scale tests and in full scale shells. Maximum fragmentation is obtained for all materials tested when a grooved slapper is used. Comparison of the data using the grooved slapper vs the baseline data indicates that one can indeed make a fairly tough steel such as 1026 perform as well in a fragmentation sense as the brittle HF-1 steel by the use of the slapper concept. The use of circumferential notches on the outer surface of the slapper disrupts the form of the shock waves in the longitudinal direction in such a way as to break up the long slender fragments usually associated with tough materials into a more desirable chunky shape. Examination of recovered fragments using either a smooth or a grooved slapper provided clear evidence that the theoretical prediction of a new mode of fracture was indeed present and contributed significantly to the increase in fragmentation. This mode of fracture, spallation, is produced by a tensile radial stress and results in a fracture surface *parallel* to the outer surface of the shell. See Figure 6. Figure 7 shows the distribution of fragment sizes for specimens which correspond closely to the data presented in Table I. Use of the grooved slapper clearly minimizes long slender

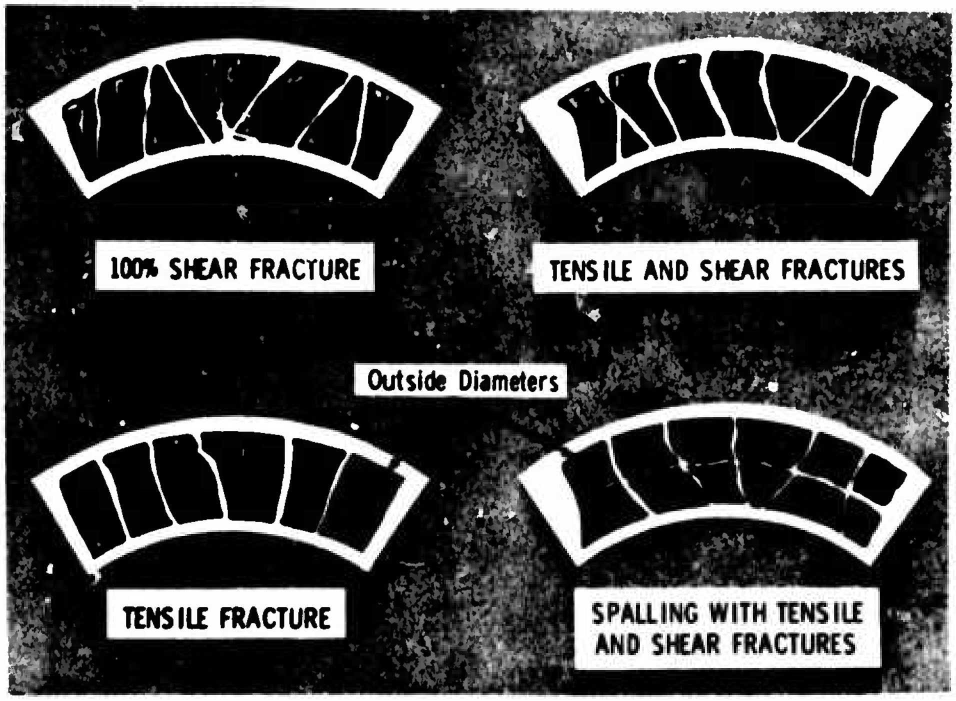


Figure 6. Typical Fragment Cross Sections

fragments and produces more of the desirable chunky size fragment even in the tough 1026 steel.

When using a slapper configuration within a given casing, the explosive charge is reduced by the volume taken by the slapper and the void. Since fragment velocity depends upon the amount of charge, the slapper does lead to a reduction of fragment velocity. By optimizing the slapper-void configuration, however it was found that this velocity reduction could be held to as little as five to ten percent. Figure 8 provides experimental and theoretical results pertinent to this aspect of the problem.

SUMMARY AND CONCLUSIONS

a. The theoretical analyses used in this report which includes wave propagation effects is significantly more realistic and provides much more quantitative detail than previous approximate analyses. Such added detail is of value not only originating improved fragmentation concepts such as the slapper but also in their optimization.

b. The use of a slapper configuration markedly increases cylinder breakup and the number of fragments produced. This increase in

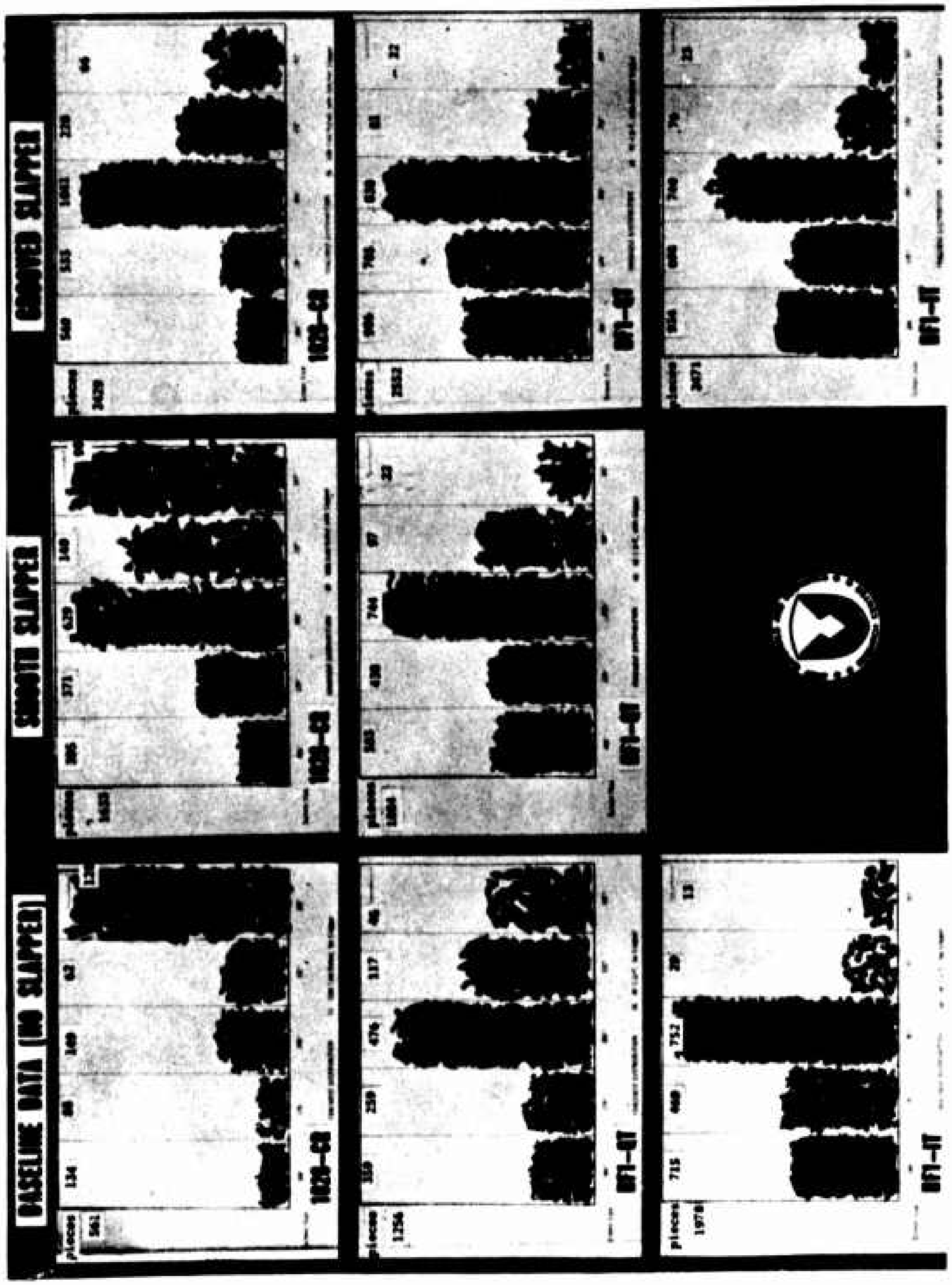


Figure 7. Frequency Distribution of Fragments

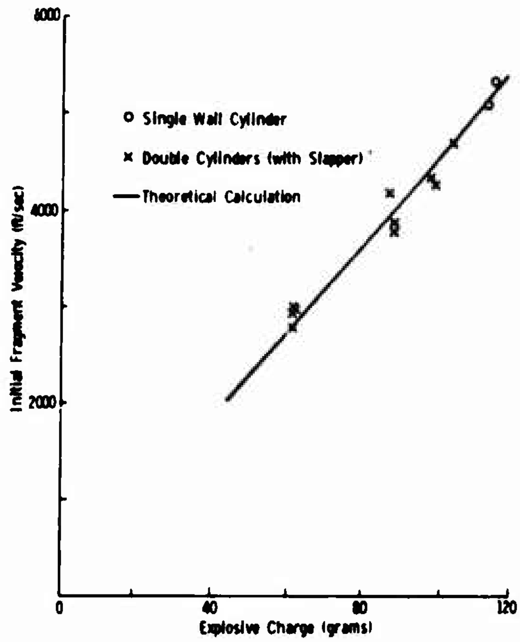


Figure 8. Influence of Explosive Charge on Fragment Velocities for Steel Casings with Constant Outer Diameter

fragmentation is directly attributable to a new mode of fracture induced by tailoring the shock waves produced in the casing.

c. The number of fragments over one-half grain in weight has been increased by a factor of as much as five in commercial low-carbon steel. A similar though more modest increase in number of fragments was obtained using a high-fragmentation steel HF-1. Thus the performance level of fairly tough commercial steels can be escalated to one comparable to that of the best (but brittle) fragmentation steels by the use of the slapper concept. This implies that the basic problem in fragmentation munitions may be resolved in favor of improved structural integrity and launch personnel safety without sacrificing good fragmentation performance at the target.

d. Use of a slapper configuration reduces the mass of explosive used, which results in a decrease in fragment velocity. However, this loss can be held to as little as five percent with no loss in fragmentation performance by optimum design of the slapper.

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